HEAVY ION BEAM PROBING – A TOOL TO STUDY GEODESIC ACOUSTIC MODES AND ALFVEN EIGENMODES IN THE T-10 TOKAMAK AND TJ-II STELLARATOR

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Heavy ion beam probing (HIBP) is a unique diagnostic for core plasma potential. It operates in the T-10 tokamak and TJ-II flexible heliac. Multi-slits energy analyzers provide simultaneously the data on plasma potential φ (by beam extra energy), plasma density (by beam current) and B_{pol} (by beam toroidal shift) in 5 poloidally shifted sample volumes. Thus, the poloidal electric field and the electrostatic turbulent particle flux are derived. The fine focused (<1 cm) and intense (100 μA) beams provide the measurements in the wide density interval n_e=(0.3...5)×10^{19} m^{-3}, while the advanced control system for primary and secondary beams provides the measurements in the wide range of the plasma currents in T-10 and magnetic configurations in TJ-II, including Ohmic, ECR and NBI heated plasmas. Low-noise high-gain (10^7 V/A) preamplifiers with 300 kHz bandwidth and 2 MHz sampling allow us to study quasi-coherent modes like Geodesic Acoustic Modes (GAMs) and Alfvén Eigenmodes (AEs). The spatial location, poloidal rotation velocity and mode numbers for GAMs and AEs were studied in the core plasmas.

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INTRODUCTION

HIBP [1, 2] is well known as a unique tool for the direct measurement of the plasma potential in the core plasma of toroidal fusion devices. HIBP successfully operated in the middle-size tokamaks like TEXT, JIPPT-2U, JFT-2M and stellarator CHS, and also in smaller devices like TJ-I tokamak and WEGA stellarator [3]. Now HIBP is in operation in the TUMAN-3M and ISSTOK tokamaks, MST reversed field pinch and LHD stellarator. There are also proposals to install HIBP in the W7-X stellarator and COMPASS tokamak and also preliminary proposals for ITER. On top of that an advanced HIBP routinely operates in the T-10 tokamak [4] and TJ-II stellarator [5]. This paper is focused in the recent HIBP advances performed at these two machines directed to study of quasicoherent modes like Geodesic Acoustic Modes (GAMs) and Alfvén Eigenmodes (AEs). GAM is a high frequency branch of the Zonal flows, which are considered to be a turbulence self-regulation mechanism [3]. There are also GAMs, which are excited by supra-thermal electrons or fast ions, appeared due to NBI heating, the so-called e-GAMs. AEs are magneto-hydrodynamic instabilities, excited by fast electrons or by fast ions appeared due to NBI or ICRF heating. AEs may affect the fast ion losses and also thermal particle losses, so affect the plasma confinement. AEs excited by fusion alphas may be dangerous for the plasma performance of future reactors. It was found that GAMs are the low-frequency limit of AEs. The importance of the GAMs and AEs for plasma confinement and the links between them claim for the diagnostic tool to study directly GAMs and AEs in the core plasma regions of fusion devices. GAMs are pronounced mostly in the plasma potential, so the application of HIBP for the GAM studies is quite natural. AEs, as the electromagnetic oscillations propagating along the magnetic field lines, manifest themselves as oscillations in plasma electric potential, poloidal magnetic field and also in plasma pressure (density). The ability of the advanced HIBP to measure these three quantities simultaneously makes it an effective tool to study AEs, their properties and location. The paper discusses the diagnostics capabilities and limitations and gives the survey of recent studies of GAM in T-10 and AE in TJ-II.

1. MULTICHANNEL ENERGY ANALYZERS IN T-10 AND TJ-II

HIBP is a direct diagnostic for studying the electric potential φ and its oscillations. It was recently upgraded to the 5-channel energy analyzer, presented in Fig. 1. In both T-10 and TJ-II the analyzers with similar design are in operation now.

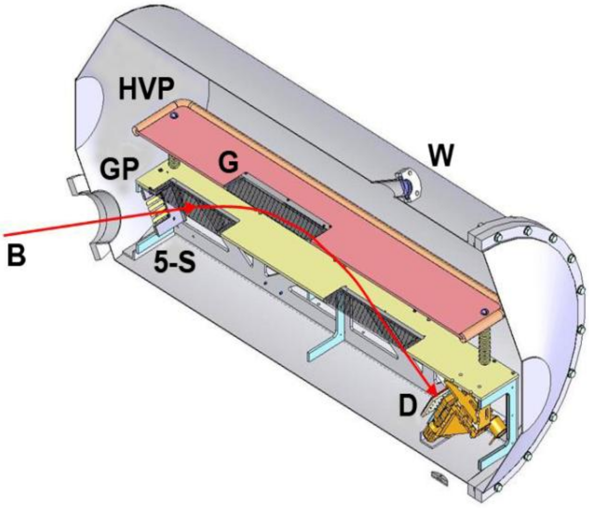

Fig. 1. The five-slit energy analyzer. B – beam; D – detectors; G – grid; GP – ground plate; HVP – high-voltage plate; W – window; 5-S – entrance slits

This new analyzer with 5 entrance slits allows us to carry out simultaneous measurements of plasma potential, density $\tilde{n}_e$ and B_{pol} in 5 neighboring sample volumes. The adjustment procedure were performed to get the location of sample volumes as close as possible to desired magnetic flux surfaces that allows us to estimate the local value of poloidal electric field

$$E_{pol} = (\varphi_1 - \varphi_2)/\delta x, \qquad (1)$$

where, δx ~1 cm. This limits the poloidal wave vector, $k_\theta < 3$ cm^{-1}. The radial $E\times B$ drift velocity is

$$V_r = E_{pol}/B_{tor}. \qquad (2)$$

Finally, the radial turbulent particle flux is

$$\boldsymbol{\Gamma_r}(t) = \tilde{n}_e \tilde{V}_r = 1/B_{tor}\ \tilde{n}_e(t)\ \tilde{\tilde{E}}_{pol}(t) = \boldsymbol{\Gamma_{E\times B}}. \qquad (3)$$

For the analysis of the flux dynamics in arbitrary units, or for frequency spectra analysis, the relative data for density oscillations $\delta n_e(t) = \tilde{I}_t(t)/\overline{I_t}$ is sufficient. In the low-density case, for the estimation of the absolute value of $\boldsymbol{\Gamma_{E\times B}}(t)$, $\tilde{n}_e$ may be replaced by $\tilde{I}_t(t)$. In the higher-density case, one should take into account the attenuation effect by the expression: $\tilde{n}_e = \tilde{I}_t/\overline{I_t}\cdot\overline{n}_e$, where oscillatory component $\tilde{I}_t/\overline{I_t}$ is measured by HIBP and normalization factor $\overline{n_e}$ is provided by other diagnostics like interferometry. This way allows us to extract $\boldsymbol{\Gamma_{E\times B}}$ for the first time in the core plasma of the T-10 tokamak [6] and the TJ-II stellarator [7].

2. GAM STUDIES IN T-10

Basic principles of HIBP measurements of plasma parameters were described in [8] in application to GAM. In T-10 we use Tl^+ ions with energy E_b up to 280 keV. Varying the beam energy and entrance angle into the plasma, we can scan the sample volume spatially and form the detector grid – the observation area in plasma. For each slit of the energy analyzer (see Fig. 1) the spatial resolution < 1…2 cm and temporal resolution <5 μs was provided at the radii 6 < r < 30 cm for B_{tor} < 2.1 T [9]. GAMs are typically observed as a pronounced monochromatic peak in the frequency power spectra of electric potential φ in the core plasma and at the edge as well [10], as presented in Fig. 2.

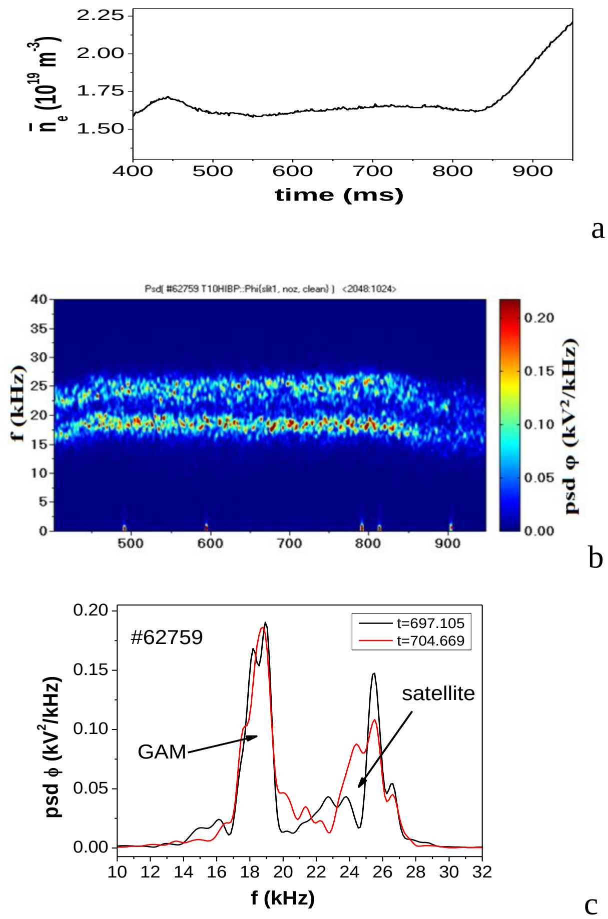

Fig. 2. Power spectrogram of plasma potential with pronounced main GAM peak and satellite, evolving in time (a); time evolution of the line-averaged density (b); two examples of the power frequency spectra (c); showing the robustness of the spectral structure of GAM

The cross-phase analysis [11] of the potential perturbation measured simultaneously in two sample volumes, separated poloidally at the same magnetic surface, shows that poloidal mode number of the GAM is zero over the observation area, as presented in Fig. 3.

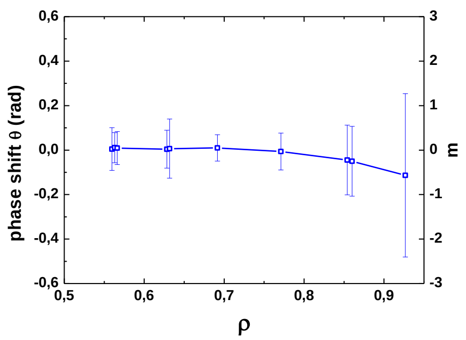

Fig. 3. Phase shift and poloidal mode number of GAM oscillations measured by 5-slits analyzer

Fig. 4 shows cumulative data over all discharges with Ohmic and ECR heating at different currents 140 < I_p < 300 kA and densities 1×10^{19} m^{-3} < $\bar{n}_e$ < 6×10^{19} m^{-3}. Fat red line corresponds to theoretical prediction:

$$f_{GAM}^{e} = \frac{1}{2\pi R}\sqrt{2T_e / m_i}\,, \tag{4}$$

dashed lines mark ±10% deviations from (4).

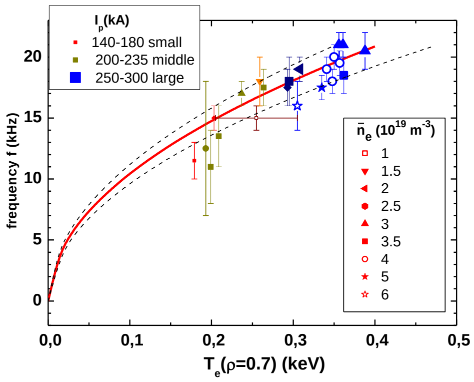

Fig. 4. Dependence of GAM frequency on the electron temperature at the radius ρ = 0.7. Cumulative data over all discharges with different currents 140 kA<I_p< 300 kA and densities 1×10^{19} m^{-3}< $\bar{n}_e$<6×10^{19} m^{-3}are marked by symbols of different sizes and colors. Lines correspond to the theoretical square root f_{GAM}^{e} dependence on T_e with 10 % variation

Fig. 4 shows the overall agreement of the observation with theoretical prediction within experimental accuracy. It was also shown with HIBP that GAM has almost constant frequency over almost whole radial range, which suggest the character of the global eigenmode [12].

3. AE STUDIES IN TJ-II

Due to its capability to measure simultaneosly potential, B_{pol} and density oscillations, HIBP is the most direct diagnostics to study AE [12], an electromagnetic wave, propagating along the magnetic field lines of plasma configuration and producing the oscillatory components of E_r, B_{pol} and plasma pressure (density). AEs are visible in all three HIBP parameters as presented in their spectrograms in Fig. 5. Various modes, marked with numbers are clearly detectable in the NBI heated phase of the discharge [13]. The time evolution of the mode frequencies follows the Alfvén law:

$$f_{AE} \approx \frac{k_{\parallel}}{2\pi}\frac{\sqrt{n_e}}{B}\,. \tag{5}$$

The spatial scan of the sample volume allows us to find a radial location for each mode, as shown in Fig. 6 [14].

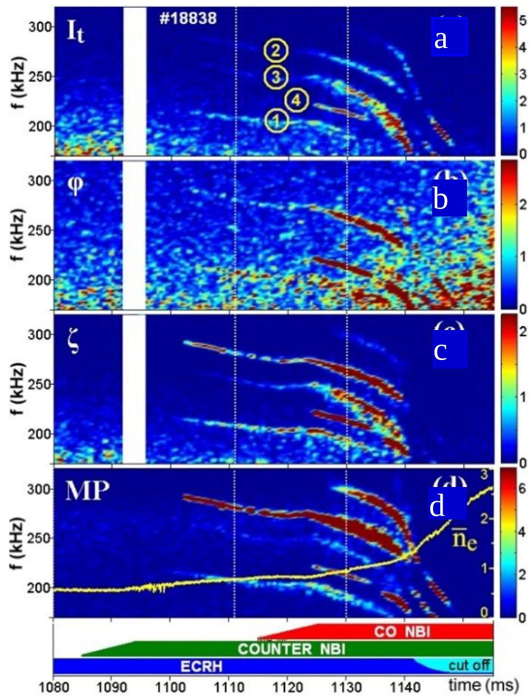

Fig. 5. PSD spectrograms of HIBP (ρ = -0.5) and Magnetic Probe (MP) signals in arb. units. Alfvén Eigenmodes are pronounced: on the total secondary beam current I_t proportional to n_e (a); on the potential φ (b); on the toroidal shift of secondary beam ζ proportional to B_{pol} (c); on the MP signal (d). Yellow curve in (d) shows the line-averaged density $\bar{n}_e$

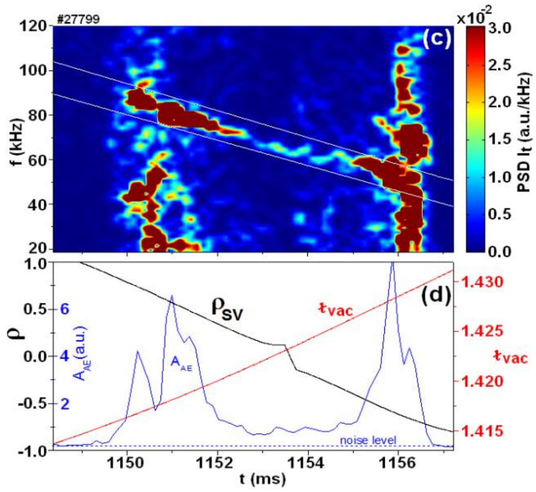

Fig. 6. The AE radial distribution measured by HIBP radial scan: the spectrogram of plasma density perturbation obtained by the radial scan from ρ_{SV} = 1 at LFS to ρ_{SV} = -1 at HFS (a); the time traces of the mode amplitude (blue) (b); corresponding to the frequencies in the marked range of panel (c); t_{vac} (0) (red), and ρ_{SV} (black)

CONCLUSIONS

HIBP was recently upgraded with the multichannel energy analyzer in T-10 and TJ-II. These advanced HIBPs appear to be the effective tool to direct internal study of GAM and AEs. The recent HIBP data proves the identification of GAM and AEs and provides the new data of the mode features, poloidal strictures and spatial location.

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ЗОНДИРОВАНИЕ ПУЧКОМ ТЯЖЕЛЫХ ИОНОВ – МЕТОД ИССЛЕДОВАНИЯ ГЕОДЕЗИЧЕСКИХ АКУСТИЧЕСКИХ И АЛЬФВЕНОВСКИХ МОД НА ТОКАМАКЕ Т-10 И СТЕЛЛАРАТОРЕ TJ-II

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Зондирование пучком тяжёлых ионов (ЗПТИ) является уникальной диагностикой для исследования потенциала горячей плазмы, она работает на токамаке Т-10 и стеллараторе TJ-II. Многощелевые анализаторы позволяют одновременно определять потенциал, плотность и полоидальное магнитное поле в пяти точках измерения в плазме, что позволяет найти полоидальное электрическое поле и турбулентный поток частиц. Хорошо сфокусированные (< 1 см) интенсивные (100 мкА) пучки позволяют вести измерения в широком интервале плотностей $\bar{n}_e$=(0.3…5)×10^{19} м$^{-3}$, а система управления первичным и вторичным пучками обеспечивает измерения в пределах изменения параметров Т-10 и TJ-II, включая режимы омического, электронно-циклотронного и инжекционного нагревов плазмы. Исследованы геодезические акустические моды и альфвеновские собственные моды частотой до 300 кГц.

ЗОНДУВАННЯ ПУЧКОМ ВАЖКИХ ІОНІВ – ЗАСІБ ДЛЯ ДОСЛІДЖЕННЯ ГЕОДЕЗИЧНИХ АКУСТИЧНИХ ТА АЛЬФВЕНОВСЬКИХ МОД НА ТОКАМАЦІ Т-10 ТА СТЕЛАРАТОРІ TJ-II

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Зондування пучком важких іонів (ЗПВІ) є унікальна система діагностики для дослідження потенціалу в гарячій плазмі на токамаці Т-10 та стелараторі TJ-II. Аналізатори з багатою кількістю апертур дозволяють одночасно вимірювати потенціал, густину та полоїдальне магнітне поле у п’яти об’ємах плазми, що дозволяє знайти полоїдальне електричне поле та турбулентний потік часток. Гарно сфокусовані (< 1 см) інтенсивні (100 мкА) пучки дозволяють провести вимірювання в широкому інтервалі $\bar{n}_e$=(0.3…5)×10^{19} м$^{-3}$ густини, а система керування первинним та вторинним пучками забезпечує вимірювання у межах діапазону зміни параметрів Т-10 та TJ-II, які включають у себе режими омічного, електронно-циклотронного та інжекційного нагрівів плазми. Досліджено геодезичні акустичні моди і альфвенівські коливання особистої моди частотою до 300 кГц.